

PRENTICE
HALL
INTERNATIONAL
EDITIONS



ENGINEERING RELIABILITY
FUNDAMENTALS AND APPLICATIONS

R. RAMAKUMAR



Contents

PREFACE	<i>xi</i>
1 INTRODUCTION AND OVERVIEW	1
1.1 Introduction	1
1.2 Historical Perspective	2
1.3 Definition of Reliability	3
1.4 The Role of Reliability Evaluation	4
1.5 Reliability Assessment	6
1.6 Scope and Organization of the Text	7
1.7 Some Important Definitions	8
1.8 Further Reading	11
2 PROBABILITY AND RANDOM VARIABLES	12
2.1 Introduction	12
2.2 Permutations and Combinations	14

- 2.3 Binomial Theorem 18
- 2.4 Ordered Samples 19
- 2.5 Probability Space 19
- 2.6 Study Approaches 20
- 2.7 Basic Properties and Rules of Probability 21
 - 2.7.1 *Probability of the Null Event, 21*
 - 2.7.2 *Probability of the Union of an Event and Its Complement, 22*
 - 2.7.3 *Conditional (or Dependent) Probability, 22*
 - 2.7.4 *Intersection of Two Events, 22*
 - 2.7.5 *Probability of Union of Nondisjoint Events, 24*
 - 2.7.6 *Bayes' Theorem, 25*
- 2.8 Random Variables 32
 - 2.8.1 *Discrete Random Variables, 34*
 - 2.8.2 *Continuous Random Variables, 35*
- 2.9 Moments of Random Variables 39
- 2.10 Extreme Values 44
- 2.11 Summary 47
 - Problems 48

3 CATASTROPHIC FAILURE MODELS AND RELIABILITY FUNCTIONS

53

- 3.1 Introduction 53
- 3.2 Relationships between the Different Reliability Functions 56
- 3.3 Alternative Approach to Reliability Functions 58
- 3.4 Typical Hazard Function 59
- 3.5 Mean Time to Failure (MTTF) 66
- 3.6 Cumulative Hazard Function and Average Failure Rate 68
- 3.7 A Posteriori Failure Probability and Wearin Period 71
- 3.8 Summary 73
 - Problems 73

4 PROBABILITY DISTRIBUTION FUNCTIONS AND THEIR APPLICATION IN RELIABILITY EVALUATION

- 4.1 Binomial Distribution 76
 - 4.1.1 *Expected Value and Standard Deviation*, 78
 - 4.1.2 *Applications*, 79
- 4.2 The Poisson Distribution 83
 - 4.2.1 *Expected Value and Standard Deviation*, 85
 - 4.2.2 *Alternative Derivation of the Poisson Distribution*, 86
- 4.3 Constant-Hazard Model and the Exponential Distribution 89
 - 4.3.1 *Expected Value and Standard Deviation*, 92
- 4.4 The Normal Distribution 95
 - 4.4.1 *Moments*, 99
- 4.5 The Uniform or Rectangular Distribution 101
- 4.6 The Rayleigh Distribution 103
 - 4.6.1 *Linearly Decreasing Hazard Model*, 104
- 4.7 The Weibull Distribution 108
- 4.8 The Gamma Distribution 114
- 4.9 The Lognormal Distribution 117
- 4.10 The Beta Distribution 120
- 4.11 Extreme-Value Distributions 122
- 4.12 The Hazard Rate Model Distribution 125
- 4.13 The General Distribution 125
- 4.14 Other Possible Models 126
- 4.15 Modeling the Wearout Region 126
- 4.16 Reliability and Maintenance 129
 - 4.16.1 *Modeling Ideal Scheduled Maintenance*, 130
- 4.17 Ideal Repair 135
- 4.18 Ideal Repair and Preventive Maintenance 138
- 4.19 Summary 139
 - Problems 139

5 COMBINATORIAL ASPECTS OF SYSTEM RELIABILITY 148

- 5.1 Introduction 148
- 5.2 Series or Chain Structure 148
- 5.3 Parallel Structure 150
- 5.4 An r -out-of- n Structure 151
- 5.5 Star and Delta Structures 152
- 5.6 Series-Parallel Structure 154
- 5.7 Triple Modular Redundancy 155
- 5.8 N -tuple Modular Redundancy 156
- 5.9 Standby Redundancy 156
- 5.10 General Techniques for Evaluating the Reliability of Complex Systems 158
 - 5.10.1 *Inspection, 158*
 - 5.10.2 *Event-Space Method, 159*
 - 5.10.3 *Path-Tracing Method, 161*
 - 5.10.4 *Decomposition Method, 161*
 - 5.10.5 *Minimal Cut Set Method, 164*
 - 5.10.6 *Minimal Tie Set Method, 165*
 - 5.10.7 *Connection Matrix Techniques, 166*
 - 5.10.8 *Event Trees, 168*
 - 5.10.9 *Fault Trees, 172*
- 5.11 Three-State Devices 179
 - 5.11.1 *Series Structure, 179*
 - 5.11.2 *Parallel Structure, 181*
 - 5.11.3 *Series-Parallel Network, 182*
 - 5.11.4 *Parallel-Series Network, 182*
 - 5.11.5 *Star-Delta Structure, 185*
- 5.12 Combinatorial Aspects of Time-Dependent Reliabilities 185
 - 5.12.1 *Series Configuration, 186*
 - 5.12.2 *Parallel Configuration, 188*
 - 5.12.3 *An r -out-of- n Structure, 191*
- 5.13 Standby Systems Modeling Based on Probability Distributions 194
- 5.14 Modeling Spares with Instant Replacement 204
- 5.15 Summary 207
 - Problems 207

6	MARKOV MODELS	222
6.1	Introduction	222
6.2	Definitions	223
6.3	Discrete Markov Chains	224
6.4	Absorbing Markov Chains	228
6.5	Continuous Markov Processes	239
6.6	Summary	249
	Problems	250
7	RELIABILITY EVALUATION OF ENGINEERING SYSTEMS USING MARKOV MODELS	256
7.1	Introduction	256
7.2	Solution of $\dot{X} = AX$	256
7.3	Steady-State or Limiting Probabilities	260
7.4	Some Useful Models and Concepts	261
	7.4.1 Binary Model for a Single Repairable Component,	261
	7.4.2 Two Dissimilar Repairable Components,	264
	7.4.3 Ternary Model for a Single Component,	267
	7.4.4 Two Identical Repairable Components,	268
7.5	Introduction to Frequency and Duration Techniques	274
7.6	General Approach to Finding the Expected Passage Time	278
7.7	General Expression for the Frequency of a State	279
7.8	Flow-Type Systems and Cumulated States	284
	7.8.1 States With Identical Capacity,	286
7.9	Mixed Product Approach	290
7.10	Frequency Balance Approach	293
7.11	More Applications of Markov Processes	295
	7.11.1 Modeling Normal Repair and Preventive Maintenance,	296
	7.11.2 Inclusion of Installation Time,	297

- 7.11.3 *Inclusion of a Spare*, 298
- 7.11.4 *Modeling Standby Systems*, 300
- 7.11.5 *Modeling Multicomponent Systems with Only One Repair Facility*, 307
- 7.12 Merging of States and Reduced Models 309
- 7.13 Markov Approach to Nonrepairable Systems 311
- 7.14 State-Space Truncation 312
- 7.15 Summary 314
- Problems 315

8 APPROXIMATE METHODS

321

- 8.1 Introduction 321
- 8.2 Components in Series 321
- 8.3 Components in Parallel 324
- 8.4 An r -out-of- n Structure 329
- 8.5 Influence of Weather 334
 - 8.5.1 *Components in Series*, 338
 - 8.5.2 *Two Components in Parallel*, 339
- 8.6 Scheduled Maintenance Outages 342
 - 8.6.1 *Components in Series*, 342
 - 8.6.2 *Two Components in Parallel*, 343
- 8.7 Overload Outages 343
- 8.8 Total Outage Rate 344
- 8.9 Markov Representation of Nonexponential Distributions 352
 - 8.9.1 *Stages in Series*, 353
 - 8.9.2 *Stages in Parallel*, 357
 - 8.9.3 *Stages in Series Terminated with Two Stages in Parallel*, 359
- 8.10 Common-Mode Failures 361
- 8.11 Rare-Event Approximations 367
- 8.12 Summary 372
- Problems 373

9	RELIABILITY AND ECONOMICS	380
9.1	Introduction	380
9.2	The Economics of Redundancy	382
	9.2.1 <i>Cost Minimization for the Unit Redundancy Configuration, 384</i>	
9.3	The Economics of Repair and Maintenance	388
9.4	Availability Analysis	390
9.5	Reliability Requirements Imposed by Economics	394
9.6	Summary	399
	Problems	400
10	ACCELERATED TESTING AND MODELS	402
10.1	Introduction	402
10.2	True Acceleration	403
10.3	Physical Acceleration and Failure Distributions	404
	10.3.1 <i>Exponential Distribution, 405</i>	
	10.3.2 <i>Weibull Distribution, 405</i>	
	10.3.3 <i>Lognormal Distribution, 406</i>	
	10.3.4 <i>Gamma Distribution, 407</i>	
10.4	Acceleration Models	410
10.5	The Arrhenius Model	411
10.6	The Eyring Model	414
10.7	Summary	415
	Problems	415
APPENDICES		
A	FUNDAMENTALS OF MATRICES	417
B	BOOLEAN ALGEBRA	427
C	THE LAPLACE TRANSFORM	429
D	DIFFERENTIAL EQUATIONS	437

x	Contents
E	SOME USEFUL DERIVATIVES AND INTEGRALS 443
F	THE BETA FUNCTION 445
G	THE GAMMA FUNCTION 447
H	TABLES OF VALUES FOR n FACTORIAL 449
I	BINOMIAL COEFFICIENTS 450
J	TABLES OF VALUES FOR THE EXPONENTIAL FUNCTIONS e^x and e^{-x} 452
K	STANDARD NORMAL CURVE AREAS 455
L	STANDARD NORMAL CURVE ORDINATES 457
	REFERENCES 459
	ANSWERS TO PROBLEMS 462
	INDEX 477